# FISHERY THRESHOLDS FOR BRISTOL BAY RED KING CRABS

By

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# EXECUTIVE SUMMARY

This report evaluates the merits of a male threshold for conservation of the Bristol Bay stock of red king crabs. Thresholds are commonly used to close fisheries to promote stock rebuilding from low levels. Two thresholds are used for Bristol Bay red king crabs: 8.4 million mature females and 14.5 million pounds of effective spawning biomass (ESB). The latter threshold is based on calculations of the number of mature females mated in any one year and assumes that mature males are capable of mating with 1-3 females. These thresholds were recommended based on simulation modeling of stock rebuilding and long-term optimal harvest strategies.

Controlled breeding studies provide somewhat disparate estimates of the breeding success of male red king crabs. Older studies in nearshore enclosed pens suggest that sublegal- and legal-sized males have high mating success with 7-9 females in a season, whereas recent studies in the laboratory found that very small sublegal males had poor success in mating more than 1 female; larger sublegal- and legal-sized males had reduced mating success after 3 mates. On the other hand, under natural conditions small males are rarely observed in mating pairs, even when small crabs predominate the population. Despite these studies, considerable uncertainty remains about red king crab reproduction in the sea: for instance, the percentage of mature males that migrate seasonally to breeding grounds and the number of females successfully mated by those males are unknown.

In the late 1960s after a period of heavy harvest in the Kodiak area, many barren females were observed owing to a shortage of mature males. Some circumstantial evidence exists that a female-predominated sex ratio was associated with declines in clutch fullness in the 1970s and 1980s. For Bristol Bay, no such evidence was found. Though clutch fullness varies annually in Bristol Bay, this was not correlated to mature female abundance, ESB, sex ratio of mature male to female crabs, nor with the ratio of male reproductive potential to mature female abundance.

The Alaska Department of Fish and Game (ADF&G) has not identified conservation concerns that warrant the recommendation of a threshold based on mature male abundance for Bristol Bay. Thus, creation of a male threshold for biological reasons would have to be primarily based on providing a buffer against wrong assumptions about king crab reproductive dynamics. For example, if the assumption that mature males mate with 1-3 females is overestimated or if males have significant difficulty finding mates at depressed stock sizes, then a threshold based on mature males could be justified.

If a decision is made to establish a closure based on males, not for conservation concerns, but due considerations of allocation or difficulty to manage toward small GHLs without overharvesting, then it is recommended that the criterion be based on a minimum GHL level rather than a mature male "threshold." Thresholds are typically reserved for use in addressing conservation concerns, such as recruitment overfishing.

# INTRODUCTION

The Alaska Board of Fisheries (BOF) will meet during August 25-27, 1997, to consider management options for the red king crab fishery in Bristol Bay. This meeting was prompted by difficulties that the Alaska Department of Fish and Game (ADF&G) encountered in attempting to manage the fishery for a 5.0 million pound guideline harvest level (GHL) during the commercial fishery in 1996. Unexpectedly high catch rates during the short fishery led to landings of 8.4 million pounds – 68% higher than the target GHL specified by the 10% mature male harvest rate designed to rebuild the stock.

At the last BOF meeting in March 1997, some representatives of the fishing industry and members of the BOF expressed interest in the possibility of establishing a minimum GHL below which the fishery would not open because it is unmanageable or perhaps uneconomical to prosecute under expected levels of fishing effort. Because this is a male-only fishery, questions also arose regarding the need to establish a male threshold to ensure conservation at depressed stock sizes.

The goal of this report is to address the merits of a male threshold for conservation of the Bristol Bay red king crab stock. Specifically, I summarize current thresholds, review investigations on the breeding success of male red king crabs, examine the evidence that mature male abundance can limit reproductive success, and evaluate the need to establish a male threshold.

# CURRENT FISHERY THRESHOLDS IN BRISTOL BAY

A *fishery threshold* is a minimum population level below which there is concern for the ability to rebuild the stock over a reasonable period of time. In fishery management, thresholds specify the stock level below which fishing is stopped to promote rebuilding. Thresholds can be used to safeguard against *recruitment overfishing*, the condition that occurs when the spawning stock is reduced to too low a level to ensure adequate production of young crabs – the future recruits to the fishery. BOF policy 90-04-FB (see p. 44-46 ADF&G 1996) directs ADF&G to use thresholds in the management of king crab fisheries in Alaska. Accordingly, thresholds are specified in state (e.g., Pengilly and Schmidt 1995) and federal crab fishery management plans (NPFMC 1989).

Two thresholds are used to manage the Bristol Bay red king crab fishery. The Crab Plan Team of the North Pacific Fishery Management Council (NPFMC 1990) calculated a threshold of 8.4 million fertilized females based on Thompson's (1990) method of applying 20% equilibrium spawning stock to a stock-recruit model. In practice, a threshold of 8.4 million mature females (>89 mm carapace length, CL) is used for Bristol Bay red king crabs on the basis that mean size of maturity for females is 89 mm CL (Otto et al. 1990) and abundance of females >89 mm CL is easier to estimate from survey data than abundance of fertilized females (Pengilly and Schmidt 1995).

In 1996, the BOF adopted thresholds for Bristol Bay red king crabs of 14.5 million pounds of effective spawning biomass[1] (ESB) and 8.4 million mature females. The ESB-based threshold resulted from Zheng et al.'s (1996b) analysis of management strategies that produce high yields while safeguarding against recruitment overfishing. The threshold of 14.5 million pounds of ESB also corresponds to a region on a stock-recruitment curve below which the ability of the stock to rebuild over a reasonable length of time is uncertain (Figure 1). Intuitively, ESB is a better index of spawning stock than the number of either fertilized females or females >89 mm CL as it accounts for the role of males in reproduction (Zheng et al. 1997). The BOF retained the previous threshold of 8.4 million mature females based on Zheng et al.'s (1996b) advice that females could be sufficient in biomass but deficient in numbers. These dual measures of threshold are used to manage the fishery at present.


# REPRODUCTIVE CAPABILITY OF MALE RED KING CRABS

Several reproductive features are relevant to the need for a male threshold: size of maturity, ability of mature males to mate with multiple females, and effects of size on male breeding success. These considerations are discussed below.

## Size of Male Maturity

"Maturity" has several operational definitions for male crabs. *Physiological maturity* occurs at a size where males produce spermatophores. In Bristol Bay, 50% of 50-59 mm CL males produced spermatophores (Paul et al. 1991). *Morphometric maturity* is the size at which the height of the chela (claw) grows at a disproportionately faster rate than overall body size. Large claws are presumed to be important for mating embraces with females. Somerton (1980) estimated the size of 50% morphometric maturity to be 103 mm CL for male red king crabs in Bristol Bay. *Functional maturity* is the observed size of males in mating pairs. Unfortunately, extensive data on red king crab mating pairs are limited to the Kodiak area. Based on grasping pair data, Schmidt and Pengilly (1990) estimated the minimum size of functional maturity to be 130 mm CL. By comparing size differences between Kodiak and Bristol Bay, Pengilly and Schmidt (1995) estimated minimum size of functional maturity to be 120 mm CL for Bristol Bay.

## Controlled Breeding Studies

Several studies have investigated the ability of male red king crabs to mate successfully with multiple females. Eleven sublegal (<145 mm CL) males and 51 females (size not reported) were collected from precopulatory mating embraces off Kodiak Island and were

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[1] *Effective spawning biomass* is the estimated biomass (weight) of mature female crabs that mature male crabs successfully mate in a given year. Depending on size, mature males are assumed to mate with 1-3 females. In most years, all females are mated and, in such case, ESB is simply the biomass of mature females.

placed in the live tank of a vessel (Powell and Nickerson 1965). After 9 days, all females produced full egg clutches, except for one that had 10% clutch fullness. Although observations on individual males were not collected, the sex ratio, 4.6 females per male, showed that males were capable of multiple matings in a short time period.

More extensive breeding experiments were conducted by Powell et al. (1974) in which the mating ability of individual males was estimated. Twenty-four total small (136-144 mm CL) and large males (150-193 mm CL) and 222 females (104-181 mm CL) were collected from grasping pairs off Kodiak Island and placed in nearshore enclosed pens for 56 days. Males were provided females at the rate of one every 5 days. Recorded measures of mating success were number of females mated as indexed by the number induced to ovulate (extrude eggs), relative clutch fullness, and percent of egg mass fertilized. The number of females induced to ovulate and clutch size declined with increasing numbers of potential mates presented to males (Figure 2). Mating success declined most sharply after 7 mates. All males mated with at least 1 female, and one large male mated with 14 females. Powell et al. (1974) found little effect of male shell condition on the results except that small oldshell males had a more rapid decline in mating success than same-size newshell males or larger males.

Two other sets of breeding experiments were conducted in the laboratory by Paul and Paul (1990, MS). In the first set of experiments, mating success of two size categories of sublegal male crabs were tested: very small (80-89 mm CL) and small (130-139 mm CL). Female mates were 102-154 mm CL. In the second set of experiments, legal (large) male red king crabs of size 140-204 mm CL were provided the opportunity to mate with 119-164 mm CL females. In both sets of laboratory experiments males were provided the opportunity to mate with up to 4 females. A mating was considered successful if the female was induced to ovulate and eggs initiated cell division. Declines in mating success with number of female mates were steeper for mating experiments conducted in the laboratory (Figure 3) than for mating experiments conducted in nearshore enclosed pens (Figure 2). Small (sublegal) and large (legal) male crabs had reduced mating success after 3 mates (Figure 3). Very small sublegal males had poor success in mating more than 1 female.

## Field Observations on Mating Red King Crabs

Field observations revealed many insights on king crab mating under natural conditions. Males are not capable of mating during the 10 day interval surrounding their molt (Powell et al. 1973). In Bristol Bay, the red king crab spawning season lasts 2-3 months, but most (80%) of females ovulate within about 20 days (FAJ 1964). Once a male finds a female, he initiates a precopulatory embrace that lasts 3-7 days through the premolt and molt stages of the female (Powell and Nickerson 1965). Mating occurs only after the female molts and ovulates (Powell et al. 1973). A female usually molts, ovulates, and mates within a 2 day period (Powell et al. 1973). Delayed mating may cause adverse effects. In one study, ovulation was incomplete if mating did not occur within 1 day of female molting (FAJ 1963),

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and in second study all females ovulated with apparently full egg clutches if mated within 9 days of molting (McMullen 1969). If females are mated >13 days after molting, no egg clutches are produced (McMullen 1969). Unmated females resorb eggs within their ovaries or extrude them on their pleopods where they decompose (McMullen and Yoshihara 1971).

Observations on 3,402 mating pairs of red king crabs were collected during spring 1963-1971 off Kodiak Island by Powell et al. (1973) and analyzed by Schmidt and Pengilly (1990). A subset of 1800 pairs comprised of oldshell males and females is shown in Figure 4. With these data Schmidt and Pengilly (1990) estimated the minimum size of functional maturity as 130 mm CL for Kodiak, because very few males smaller than 130 mm CL were found in these grasping pairs. In fact, most males in these pairs were >163 mm CL.

In one subset of these observations collected during December 1970 to March 1971 in Middle Bay, Kodiak Island, Powell et al. (1973) compared the size distribution of 54 mating pairs to the size distribution of 14,635 crabs collected by pot fishing and SCUBA. Most (65%) female graspees were pubescent or primiparous (remainder were multiparous)[2] and therefore small (84-119 mm CL) compared to multiparous females which were mostly 120-145 mm CL. Despite the small average size of mating females and the dominance (>95%) of males <110 mm CL in the population of males in Middle Bay, only 0.2% of the grasping males were <110 mm CL. Grasping males averaged 42 mm CL larger than their female partners and the majority of these males were 123-159 mm CL.

## Comparison of Controlled Breeding Studies and Field Observations

Clearly, males as small as 80-89 mm CL are capable of successful mating in enclosed pens (Powell et al. 1973) and laboratories (Paul and Paul 1990). Yet, field data show that males <110 mm CL are extremely rare in grasping pairs (Figure 4) even when males of this size range are the predominate size in the population (Powell et al. 1973). It is conceivable that small males are capable of mating, but are displaced by large males in the wild. However, Powell and Nickerson (1965) observed considerable fighting and partner exchange in captivity, but did not observe such exchanges in the natural environment.

Powell et al. (1973) offered two explanations for these size differences of mating males. First, molt timing of small males and females is often synchronous. Because males cannot mate for 10 days while in the softshell condition and because females must be mated within 13 days of molting, many small males may be unable to mate with pubescent females. Second, small males grasp mates 34% of the time compared to 80% of the time for large males (Powell et al. 1973). Less time spent grasping the female could provide more opportunity for the female to escape thereby reducing mating by small males under natural conditions. Because females were confined in laboratory and enclosed pen studies, they had no ability to escape even if not being grasped. Less time spent grasping may also provide increased opportunity for larger males to displace smaller males. Such replacement

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[2] Pubescent (primiparous) females are small females mating for the first time. They molt and mate prior to females that were mated the previous year (multiparous females) who must hatch their eggs prior to mating.

is not possible in controlled studies where ingress is prohibited by the walls of enclosed pens or laboratory tanks. Thus, mating success of small males may be overestimated by controlled studies where females are held captive and large males are excluded.

Another possible explanation is that small, newshell males have low levels of a reproductive hormone and lack interest in mating under natural conditions. Laufer et al. (1996) found evidence for a reproductive hormone, methyl farnesoate (MF) in *Chionoecetes bairdi, C. opilio,* and *Libinia emarginata.* MF was present at low levels in newshell males and high levels in oldshell males. In these species, oldshell males most actively mate with females. Interestingly, small males that have oldshells only attempt mating if in isolation and do not attempt to compete with larger males (Sagi et al. 1994). It is unknown if these results apply to red king crabs. However, large oldshell males are an important component of mating pairs (Figure 4), and small male red king crabs rarely skip molt. Thus, it is possible that a higher level of MF in oldshell than newshell male king crabs could partly account for disproportionately low numbers of small mature male red king crabs in mating pairs at sea.

Differences in mating success between studies conducted in nearshore enclosed pens (Powell et al. 1974) and laboratory tanks (Paul and Paul 1990, MS) are somewhat difficult to reconcile. Powell et al. (1974) concluded that sublegal- and legal-sized males are capable of high mating success with 7-9 females. This contrasts with conclusions of Paul and Paul (1990, MS) that sublegal- and legal-sized males cannot be counted on to breed more than 1-2 or 3 females, respectively, during the peak mating season.

Several factors may contribute to the differences in results. Methodology may explain some of the differences. Paul and Paul (1990, MS) estimated the mating success partly from the percentage of eggs that initiated division to the 4-64 cell stage. Powell et al. (1974) estimated percent clutch fullness and percent egg mass fertilized. Paul and Paul (MS) questioned the determinations of fertilization by Powell et al. (1974). Apparently, unfertilized eggs divide and breakdown products of rotting eggs can look like cell division to the untrained observer (Dr. A.J. Paul, University of Alaska Fairbanks, personal communication). This fact was unknown in the 1970s.

Another factor could relate to differences in the females used in these studies. It appears that most of the females studied by Powell et al. (1974) were pubescent whereas those of Paul and Paul (1990, MS) were multiparous. If so, studies on pubescent females may overstate the males' reproductive success relative to males that mated with multiparous females. Yet, male mating history may be a more important factor (Dr. A.J. Paul, University of Alaska Fairbanks, personal communication).

A problem common to all controlled experiments is that they make no accounting for the proportion of mature males that actually migrate to areas with concentrations of reproductively-active females, the search time required to find a female, the full duration of the precopulatory embrace, and the synchrony in female molt timing. In the controlled studies, females in premolt condition were artificially supplied to males; males spent no time

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searching for them. In the case of the nearshore enclosed pen studies, females were presented to males at the rate of one per 5 days. This may exaggerate the mating opportunities of males that need to locate and attend to females for longer periods of time under natural conditions. Obviously, males that do not participate in the spawning migration may not have opportunity to mate. Moreover, the ability of males to mate with multiple females is constrained by the short, 20-day peak breeding period for multiparous females.

Given these inconsistencies, Zheng et al. (1995a,b) were faced with a dilemma regarding the development of a stock-recruitment model for red king crabs in Bristol Bay. Zheng et al. (1995a) took a conservative interpretation of laboratory and shallow-water experiments in enclosed pens. Although Powell et al. (1974) found that large males can mate with 7-9 females when provided ready access to receptive females, these findings were considered to overestimate the average breeding success of male red king crabs under natural conditions. Reasons included: (1) ovulation may be incomplete if mating does not occur within 1 day of the female's molt; (2) a male's precopulatory embrace of a female lasts 3-7 days; (3) old shell males may be more important in mating; and (4) laboratory mating studies do not consider the time for males to locate mature females under natural conditions in the wild prior to courtship behavior. In calculating ESB to develop the stock-recruitment model, the number of female mates was assumed to be an increasing function of mature male size from 1 female for small mature males (120 mm CL) up to 3 females for large mature males (>160 mm CL). *Male reproductive potential* is defined as the mature male abundance by size multiplied by the maximum number of females with which a male of a particular length can mate (Zheng et al. 1995a). This assumption seems reasonable, given Paul and Paul's (MS) latest findings for legal-sized males.


## CAN MALES BE LIMITING?

### Kodiak Island

Compelling evidence that males can be limiting to reproductive success exists for red king crabs off Kodiak Island. Harvests of red king crabs from Kodiak peaked at 96 million pounds in 1965-1966. During fall 1966, Kodiak fishers began to report incidental capture of mature females without eggs (McMullen and Yoshihara 1969). Extensive sampling during spring (McMullen 1968) and fall 1968 (McMullen and Yoshihara 1969) found large concentrations of unmated mature females along the southeast side of Kodiak Island. During April-May 1968, trawl sampling found that 76.1% of mature females in Kaguyak Bay inside Twoheaded Island were not carrying eggs and had not been mated. Female:male sex ratio in this bay was 72:1. At Ocean Bay, Sitkalidak Island, 60% of mature females lacked eggs and female:male sex ratio was 40:1. On Marmot Flats, 31% of mature females lacked eggs. Later that year, in October-November 1968, 13.6% of females collected along the east and south sides of Kodiak Island did not carry eggs or carried dying eggs and decomposing egg membranes (McMullen and Yoshihara 1971). Also in October-November 1968, sampling aboard

fishing vessels revealed 72% of females in the area of Twoheaded Island and >30% of females at Tugidak, Sitkalidak and Marmot Islands were unmated (McMullen and Yoshihara 1969). These unusual percentages of unmated females along the southeast side of Kodiak were attributed to heavy fishing (including sublegal male harvest) in this area during 1964-1967 (Powell et al. 1973, McMullen and Yoshihara 1969). Unfavorable environmental conditions and disease were ruled out as alternative explanations (McMullen and Yoshihara 1971). In 1983-1984 an outbreak of a nemertean worm *(Carcinomertes regicides)* predator on red king crab eggs occurred in some areas in Alaska (Kuris et al. 1991). However, it is unlikely that nemerteans contributed materially to the regional observations on barren females in the Kodiak area in the late 1960s, because: (1) areas with abundant nemerteans are limited to narrow fjords and passages often with shallow sills; (2) close inspections of clutches at the time did not reveal any worms; and (3) prevalence of females with resorbing eggs in their ovaries confirm that barrenness was caused by lack of egg extrusion not predation on extruded eggs.

Unfortunately, assessment surveys off Kodiak did not begin until 1973 after the heyday of the fishery. Assessment surveys showed that female:male sex ratio increased from ≈0.5:1 during 1973-1975 to ≈3:1 in 1986. Legal male harvest rates >80% in the early 1980s (Collie and Kruse 1997) were associated with the skewed sex ratio. During this time, clutch fullness decreased. Nearly all females had clutches that were 90-100% full during 1973-1975, but a decline occurred through 1985 when only 15% of females had 90-100% clutch fullness (Becker et al. 1990). Egg predation by nermerteans may have contributed to reduced clutches at the end (1983-1985) of this period.

**Bristol Bay**

Unlike Kodiak, high percentages of barren mature female red king crab were not observed In Bristol Bay in the 1960s (McMullen and Yoshihara 1969). Estimates of mean female clutch size averaged 81% and varied between 43-97% in Bristol Bay during 1975-1996 (Figure 5). Fluctuations appear to be nearly random with no major trends over time. In comparison, the ratio of male reproductive potential to mature female abundance increased during the 1970s, declined in the early 1980s, generally increased until 1990, and declined thereafter (Figure 5). Trends in mature female abundance and ESB are quite different with a major increase until the late 1970s, a major decline to the early 1980s, and relatively stable through 1996 (Figure 5). Thus, there is no obvious relationship between clutch fullness and ratio of male reproductive potential to mature female abundance nor between clutch fullness and ESB (Figure 6).

Annual fluctuations in clutch size for Bristol Bay red king crabs (Figure 5) remain unexplained. It is possible that a combination of factors have resulted in these changes, including small-scale variation in sex ratio due to geographic distribution of mature males and females, timing of oceanographic cues to spawning, and synchrony of molting related to bottom temperatures. Some fluctuations in clutch size may not reflect

meaningful differences. Eggs are sloughed off over time during the ≈1 year they are carried by the female, so estimated clutch fullness values can vary depending on when the survey is conducted. Further, estimation of clutch fullness is somewhat subjective, and differences may be partly attributable to different observers.

During the 1997 stock assessments, Zheng et al. (1997) estimated that ESB could have been limited by low male reproductive potential in 7 years during 1972-1997: 1972-1974, 1977, 1981-1982, 1984, and 1997. Clutch fullness estimates are not available for 1972-1974, and estimates for 1997 are unavailable at the present time. During 1977, 1981, 1982 and 1984, estimated proportionate clutch fullness was 0.93, 0.92, 0.82, and 0.90, respectively. The mean clutch fullness for these 4 years was 0.89 whereas the grand mean during 1975-1996 was 0.81. Thus, reduced male reproductive potential was not associated with reduced clutches.

## IS A MALE THRESHOLD NEEDED?

In considering the merits of a male threshold for Bristol Bay red king crabs, the following should be kept in mind. First, the threshold of 14.5 million pounds of ESB incorporates both sexes, and is defined as the estimated biomass of mature female crabs that mature male crabs could successfully mate in a given year. If too few males are available to mate with all females, then ESB is reduced. For example, if the biomass of mature females is just above 14.5 million pounds, but males are deficient, then ESB may be reduced below threshold and the fishery would remain closed.

Unfortunately, it is not possible to establish a one-to-one relationship between ESB and mature female abundance. The reason is that abundance is measured in numbers of crabs whereas ESB is measured as biomass calculated as abundance multiplied by average weight. During periods of strong recruitment, mean weight of mature females declines, so more females are required to meet the 14.5 million pound threshold. During periods of poor recruitment, mean size of females increases, and fewer females are needed to achieve the ESB threshold. The other threshold, 8.4 million mature females, was retained in the current harvest strategy as an added conservation measure when females are plentiful in weight but deficient in numbers. After an extended period of recruitment failure, the female population shifts to larger crabs that may have reduced reproductive capacity as they senesce with old age.

It should also be pointed out that a male threshold is used for some king crab fisheries. Examples include St. Matthew and Pribilof Islands blue king crab fisheries (Pengilly and Schmidt 1995). The reason for the male threshold in these fisheries is that reliable estimates of female abundance are unavailable, so a female threshold is not practical.

A male threshold would add another measure of conservatism. Zheng et al. (1996b) based their recommendations on the 14.5 million pound ESB threshold from

simulations that considered the effects of harvest on male reproductive potential, stock rebuilding, and optimal long-term yields. Results depend on the assumption about a male's ability to mate with 1-3 females in a season. If for some reason this overestimates the number of females mated per male under natural conditions, then a male threshold has merit. For instance, it is conceivable that potential mates have difficulty finding each other at low population densities resulting in fewer females mated per male. Unfortunately, no studies have been conducted on the ability of males to locate females under different stock levels.

For sake of argument, assume that mature males can mate with only one female. In such case, rather than comparing male reproductive potential based on 1-3 potential mates to mature female abundance, we instead are interested simply in the ratio of mature male to mature female abundance (Figure 7). A couple of observations can be made. First, since 1972, mature male to mature female sex ratio has been 0.31 to 1.28. Sex ratio was below 1:1 every year except 1986 and 1990. This is a consequence of male-only fisheries. Another observation is that there appears to be no correlation between sex ratio and clutch fullness. In fact, some years of highest male:female sex ratio have the lowest mating success as indicated by clutch fullness (Figure 7).


## EFFECTS OF A MALE THRESHOLD ON THE STOCK AND FISHERY

The effects of establishing a mature male threshold depend on the level chosen. A male threshold that is so low that it is never achieved will have no benefits nor costs. A male threshold that results in additional fishery closures beyond those caused by threshold for mature females or ESB would be expected to improve the rate of stock rebuilding and increase the frequency of fishery closures. However, without conducting detailed simulations of specific alternatives, it is not possible to quantify the degree of improvements in stock status nor to determine whether there would be a long-term increase or decrease on mean yield from the fishery.

It may be informative to examine the estimated abundance of mature males, mature females, and ESB in the context of historical fishery closures for Bristol Bay red king crabs (Table 1). The fishery was closed in 1983 based on concern about the depressed status of stocks; a threshold had not yet been established at that time. In 1994 and 1995, the fishery was closed because abundance estimates of mature females available at that time were below the 8.4 million mature female threshold. Note that estimates of female abundance in 1994-1995 from the most recent stock assessment results were above threshold (Table 1).

Had the 8.4 million mature female threshold been in place since 1972, closure would have also been triggered in 1985 (Table 1). Female abundance was slightly above threshold in 1986. Since establishment of the 14.5 million pound ESB threshold in 1995, no closures have been triggered by this threshold. However, had this threshold been established in 1972, closure would have been triggered in 1985 and 1986.

As a point of departure, if a mature male threshold was established at 8.4 million mature males (the same as females), fishery closures would have been triggered in 1984 and 1985, thus such a threshold would have added one more year of closure (1984) to those triggered by thresholds for mature females or ESB. Mature male abundance was just slightly above 8.4 million in 1994-1996 (Table 1). However, if the clock was turned back to 1996, based on last year's stock assessment estimates (see Table 1 in Zheng et al. 1996a), mature males were estimated to be below 8.4 million in 1994-1996. Thus, in practice, if a 8.4 million mature male threshold was in place historically, a male threshold would have been associated with closures in 1994, 1995, and 1996. Only one of these years (1996) would have been solely caused by the mature male threshold. Just as with this example of 8.4 million mature males, by choosing larger or small mature male thresholds, a qualitative assessment of the effects can be made. Of course, this static look at the history of the fishery is imprecise. It is quite likely that additional closures in the mid-1980s would have had beneficial effects of stock sizes in the 1990s. Thus, the recent fishery closures may have been avoided.

Another benchmark against which to consider a male threshold is the number of mature males needed to ensure that the ESB threshold level (14.5 million pounds) of mature females is successfully mated. This is complex, because the number of females equating to 14.5 million pounds depends on the mean size of females, and the number of males needed to successfully mate with this number of females depends on the size distribution of mature males and their size-dependent mating ability. However, LBA allows us to make these calculations (Table 2).

The number of mature females equating to 14.5 million pounds of ESB averages 8.24 million females over 1972-1997.[3] This number of females varies annually from 6.6 million females (mean weight of 2.2 pounds) to 9.9 million females (mean weight of 1.5 pounds). Periods of poor recruitment (Table 1) are associated with higher than average mean weight of mature females (Table 2). Based on Zheng et al.'s (1995a) mating schedule of 1-3 females per male, mature males mated with an average of 1.7 females during 1972-1997. However, the average number of mates per male varied annually between 1.4-2.0 females depending on changing mature male size distributions. Based on these calculations, the number of mature males needed to mate with a 14.5 million pound ESB threshold level of females ranged between 3.5-7.2 million mature males with a long-term mean of 5.0. Mature male abundance declined below 7.2 million crabs in only one year (1985) and has not dipped below 5.0 million mature males over the history of estimates (Table 1).

There may be good cause to close the fishery based on male abundance for reasons other than conservation. For instance, small GHLs may render the fishery uneconomical for some portions of the fleet. Thus, allocation effects result from decisions to open a fishery on a small GHL or to forego the fishery until some subsequent year when the GHL could be raised. Also, in 1996, ADF&G found that small GHLs may be unmanageable under normal

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[3] This number compares favorably to the 8.4 million mature female threshold that was computed in 1995 as a long-term mean with a shorter data series.

levels of fishing effort. In 1996, the 5.0 million pound GHL was exceeded by 3.4 million pounds. As it turned out recruitment from the 1990 year class in 1997 was strong (Zheng et al. 1997), so, fortuitously, effects of this overharvest on stock rebuilding were minimized. However, failing such a year class, the consistent overharvest on a yearly basis would slow stock recovery considerably. If a decision is made to establish a closure based on males for allocation or "manageability" considerations, it is recommended that the closure criteria should be based on a minimum GHL level rather than a mature male "threshold". There are two reasons for this advice. First, there is no one-to-one relationship between GHL and mature male abundance. The GHL calculation is based not only on mature male abundance, but also on harvest rate, average weight, and legal male abundance. Second, thresholds are typically reserved for use in addressing conservation concerns, such as recruitment overfishing.

# SUMMARY

Controlled breeding studies provide somewhat disparate estimates of the breeding success of male red king crabs. Older studies in nearshore enclosed pens suggest that sublegal- and legal-sized males have high mating success with 7-9 females, whereas recent studies in the laboratory show that very small sublegal males had poor success in mating more than 1 female, and larger sublegal- and legal-sized males had reduced mating success after 3 mates. On the other hand, small males are rarely observed in mating pairs under natural conditions even when the local population of males is dominated by small crabs.

Current thresholds for Bristol Bay red king crabs include 8.4 million mature females and 14.5 million pounds of ESB based on the biomass of mature females estimated to have been mated by mature males in a given year. These thresholds were recommended based on simulation modeling of rebuilding and long-term optimal harvest strategies. In conducting these simulations, ESB was calculated assuming that males are capable of mating with 1-3 females depending on male size. This assumption was made after considering conflicting estimates of male breeding success among controlled experiments and other caveats to extrapolation of laboratory results to natural crab populations.

Strong evidence exists that high levels of unmated females in the Kodiak area in the late 1960s resulted from shortage of mature males after a period of heavy harvest. Also, circumstantial evidence exists that a female-dominated sex ratio was associated with declines in clutch fullness in the 1970s and 1980. Though clutch fullness varies annually among female red king crabs in Bristol Bay, clutch fullness does not correlate with mature female abundance, ESB, sex ratio of mature male to female crabs, nor with the ratio of male reproductive potential to mature female abundance.

The Bristol Bay red king crab fishery was closed in 1983 due to poor stock condition (no threshold had yet been established) and in 1994 and 1995 because abundance estimates of mature females available at the time were below 8.4 million. Had this female threshold

been in place since 1972, one more year of closure (1985) would have been triggered. No closures have been triggered by the 14.5 million pound threshold for ESB since establishment in 1995. However, had this ESB threshold been in place since 1972, closure would have been triggered in 1985 and 1986. By way of example, if a male threshold had been established at 8.4 million mature males – the same as mature females – this conservation measure would have been associated with fishery closures in 1984, 1985, 1994, 1995, and 1996. In 1985, 1994 and 1995, the fishery would have been closed anyway based on thresholds for mature females and/or ESB. Closures in 1984 and 1996 would have been based only on this mature male threshold.

## CONCLUSIONS AND RECOMMENDATIONS

- Unlike the Kodiak area, historical evidence for deficient numbers of mature male red king crabs has not been found for Bristol Bay. Existing thresholds based on mature female abundance and ESB levels buffer the stock against recruitment overfishing. Therefore, ADF&G does not recommend a threshold for mature males to conserve this stock.

- Creation of a male threshold for conservation purposes should be based on need to provide an additional safeguard against wrong assumptions about king crab reproductive dynamics. For example, if concern exists that mature males cannot mate with 1-3 females on average or that males have significant difficulty finding mates at depressed stock sizes, then a threshold based on mature males could be justified.

- If a decision is made to establish an additional closure trigger based on males, not for biological considerations, but to address allocation issues or difficulty to manage to small GHLs without unacceptable risk of overharvest, then it is recommended that closure criteria should be based on a minimum GHL level rather than a mature male "threshold". Thresholds are typically reserved for use in addressing conservation concerns, such as recruitment overfishing.

## ACKNOWLEDGMENTS

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Table 1. Annual abundance estimates (millions of crabs), effective spawning biomass (millions of pounds), and 95% confidence intervals for red king crabs in Bristol Bay estimated by length-based analysis by Zheng et al. (1997). Size measurements are mm CL.

| | | Males | | | | | Females | |
|---|---|---|---|---|---|---|---|---|
| Year mm→ | Recruits | Small (95-109) | Prerec. (110-134) | Mature (>119) | Legal (>134) | Recruits | Mature (>89) | Effective Spawning Biomass |

a. Abundance Estimates and Spawning Biomass

| Year | Recruits | Small (95-109) | Prerec. (110-134) | Mature (>119) | Legal (>134) | Recruits | Mature (>89) | Effective Spawning Biomass |
|---|---|---|---|---|---|---|---|---|
| 1972 | NA | 13.464 | 14.991 | 18.433 | 9.961 | NA | 59.707 | 55.245 |
| 1973 | 29.811 | 20.650 | 26.089 | 22.472 | 10.748 | 33.008 | 69.927 | 63.239 |
| 1974 | 20.597 | 14.965 | 34.825 | 34.019 | 14.765 | 28.116 | 71.392 | 93.396 |
| 1975 | 31.872 | 22.002 | 35.960 | 41.038 | 20.529 | 21.843 | 66.061 | 116.536 |
| 1976 | 43.370 | 30.094 | 45.295 | 48.753 | 25.389 | 34.445 | 75.388 | 129.274 |
| 1977 | 50.127 | 35.085 | 59.024 | 61.512 | 30.187 | 71.964 | 118.627 | 163.650 |
| 1978 | 19.138 | 14.940 | 57.518 | 74.237 | 39.244 | 46.214 | 119.529 | 199.305 |
| 1979 | 12.362 | 9.073 | 36.303 | 72.408 | 46.642 | 18.774 | 92.812 | 166.543 |
| 1980 | 23.364 | 16.003 | 25.500 | 58.568 | 43.446 | 35.932 | 93.529 | 166.120 |
| 1981 | 17.187 | 12.397 | 17.016 | 18.025 | 9.415 | 13.544 | 71.479 | 58.281 |
| 1982 | 22.985 | 15.986 | 16.028 | 10.018 | 2.917 | 17.362 | 29.972 | 23.567 |
| 1983 | 13.101 | 9.698 | 13.690 | 8.857 | 2.433 | 4.784 | 10.050 | 16.759 |
| 1984 | 18.503 | 12.849 | 12.908 | 8.082 | 2.337 | 11.729 | 13.497 | 16.337 |
| 1985 | 8.951 | 6.752 | 10.460 | 6.799 | 1.787 | 4.585 | 6.950 | 10.411 |
| 1986 | 5.865 | 4.416 | 12.250 | 11.434 | 4.236 | 3.787 | 8.911 | 14.180 |
| 1987 | 6.170 | 4.424 | 10.793 | 13.273 | 6.433 | 8.446 | 15.031 | 23.792 |
| 1988 | 5.834 | 4.209 | 9.806 | 13.868 | 7.898 | 5.475 | 16.567 | 27.787 |
| 1989 | 4.739 | 3.468 | 8.998 | 14.891 | 9.340 | 5.342 | 17.596 | 30.800 |
| 1990 | 1.377 | 1.187 | 6.912 | 14.554 | 9.867 | 0.891 | 13.910 | 26.946 |
| 1991 | 4.058 | 2.769 | 4.999 | 11.709 | 8.403 | 3.758 | 14.075 | 27.401 |
| 1992 | 5.355 | 3.765 | 5.914 | 9.859 | 6.739 | 3.532 | 13.949 | 27.396 |
| 1993 | 1.958 | 1.841 | 6.636 | 9.935 | 6.014 | 2.268 | 12.594 | 25.596 |
| 1994 | 0.934 | 0.879 | 5.224 | 8.517 | 4.839 | 0.430 | 9.760 | 21.457 |
| 1995 | 2.419 | 1.722 | 4.111 | 8.476 | 5.643 | 1.793 | 9.034 | 19.783 |
| 1996 | 3.336 | 2.453 | 4.457 | 8.530 | 5.925 | 3.844 | 10.535 | 21.258 |
| 1997 | 23.113 | 15.459 | 11.674 | 10.495 | 5.858 | 15.910 | 23.699 | 31.415 |

b. 95% Confidence Limits in 1997

| | Recruits | Small (95-109) | Prerec. (110-134) | Mature (>119) | Legal (>134) | Recruits | Mature (>89) | Effective Spawning Biomass |
|---|---|---|---|---|---|---|---|---|
| Lower | 20.544 | NA | 9.848 | 8.726 | 4.838 | 12.013 | 19.111 | NA |
| Upper | 26.649 | NA | 12.629 | 11.143 | 6.511 | 21.329 | 29.459 | NA |

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Table 2. Average weight (pounds) of mature females, number of mature females (millions) equal to 14.5 million pounds of ESB, average number of mates per mature male, and number of mature males (millions) needed to mate with 14.5 million pounds of ESB for red king crabs in Bristol Bay estimated by length-based analysis.

| Year | Mat. Female Ave. Weight (lbs) | Mat. Females Equal to 14.5 M lbs | Ave. Mates per Mature Male | Mat. Males Needed for 14.5 M lbs ESB |
|---|---|---|---|---|
| 1972 | 1.78 | 8.149 | 1.68 | 4.842 |
| 1973 | 1.71 | 8.498 | 1.64 | 5.176 |
| 1974 | 1.72 | 8.424 | 1.59 | 5.288 |
| 1975 | 1.76 | 8.220 | 1.64 | 5.021 |
| 1976 | 1.71 | 8.456 | 1.68 | 5.036 |
| 1977 | 1.60 | 9.039 | 1.65 | 5.464 |
| 1978 | 1.67 | 8.696 | 1.69 | 5.145 |
| 1979 | 1.79 | 8.081 | 1.84 | 4.392 |
| 1980 | 1.78 | 8.164 | 2.01 | 4.069 |
| 1981 | 1.90 | 7.647 | 1.72 | 4.453 |
| 1982 | 1.67 | 8.667 | 1.39 | 6.224 |
| 1983 | 1.67 | 8.695 | 1.37 | 6.349 |
| 1984 | 1.46 | 9.943 | 1.39 | 7.179 |
| 1985 | 1.50 | 9.680 | 1.36 | 7.133 |
| 1986 | 1.59 | 9.112 | 1.45 | 6.267 |
| 1987 | 1.58 | 9.161 | 1.57 | 5.823 |
| 1988 | 1.68 | 8.645 | 1.69 | 5.105 |
| 1989 | 1.75 | 8.284 | 1.81 | 4.584 |
| 1990 | 1.94 | 7.485 | 1.90 | 3.930 |
| 1991 | 1.95 | 7.448 | 1.96 | 3.799 |
| 1992 | 1.96 | 7.383 | 1.94 | 3.806 |
| 1993 | 2.03 | 7.134 | 1.84 | 3.885 |
| 1994 | 2.20 | 6.596 | 1.75 | 3.768 |
| 1995 | 2.19 | 6.621 | 1.87 | 3.544 |
| 1996 | 2.02 | 7.186 | 1.93 | 3.721 |
| 1997 | 1.66 | 8.751 | 1.80 | 4.864 |
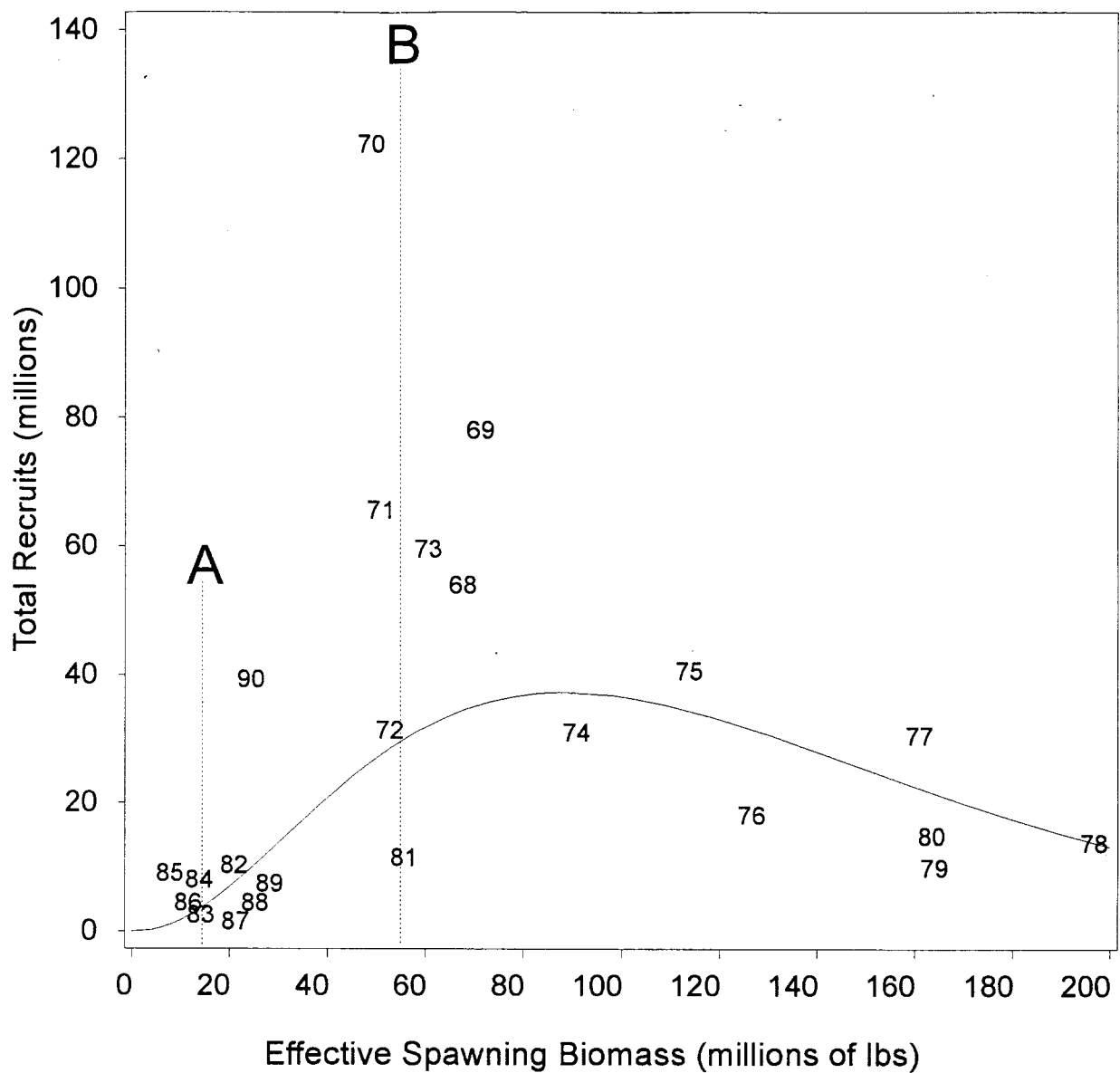
Figure 1. Stock-recruit relationship for Bristol Bay red king crabs from Zheng et al. (1997). Recruits are age 6.2 from date of hatching corresponding to a 7-year lag from spawning to recruitment. Numbers refer to year of spawning. Effective spawning biomass is defined in the text. Vertical dotted line A shows the fishery threshold of 14.5 million pounds and B shows the target rebuilding level of 55 million pounds of effective spawning biomass.
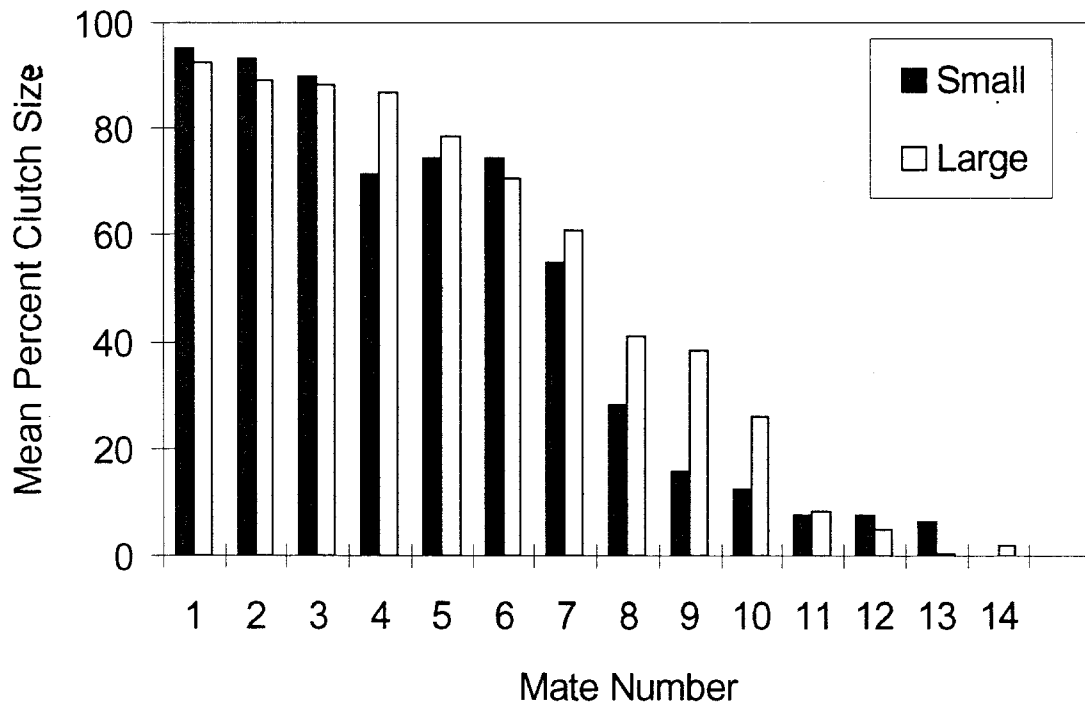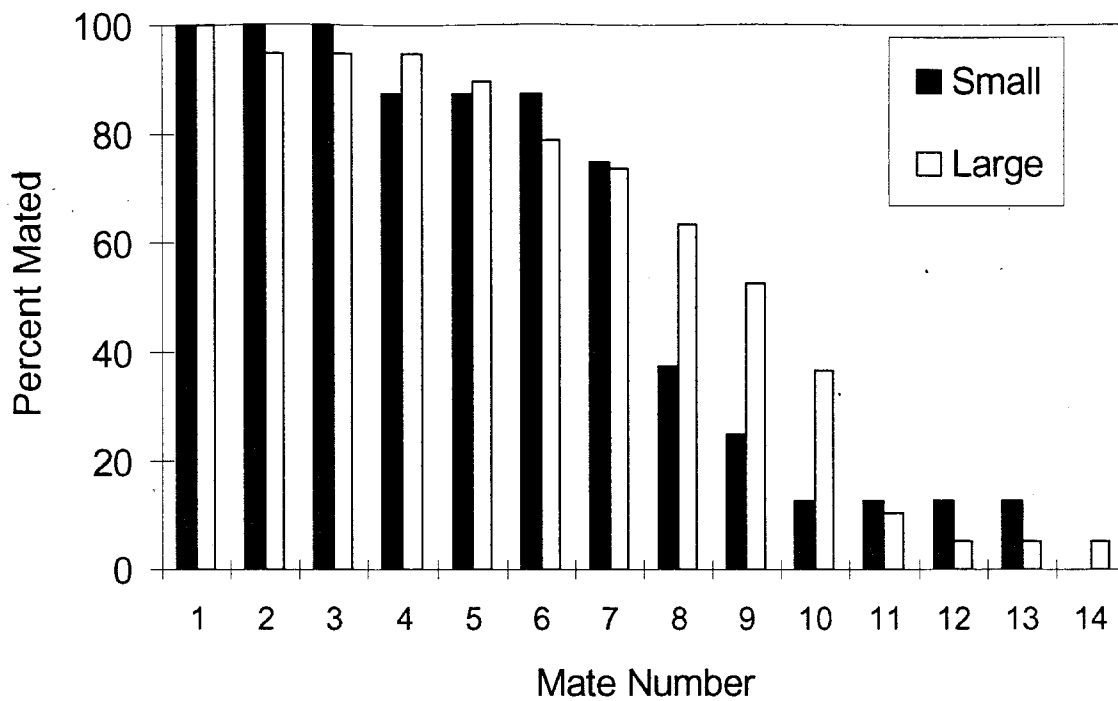
Figure 2. Percentage of females induced to ovulate (top panel) and mean percent clutch size (bottom panel) by small (136-144 mm CL) and large male red king crabs (150-193 mm CL) from mating studies conducted in enclosed nearshore pens by Powell et al. (1974).
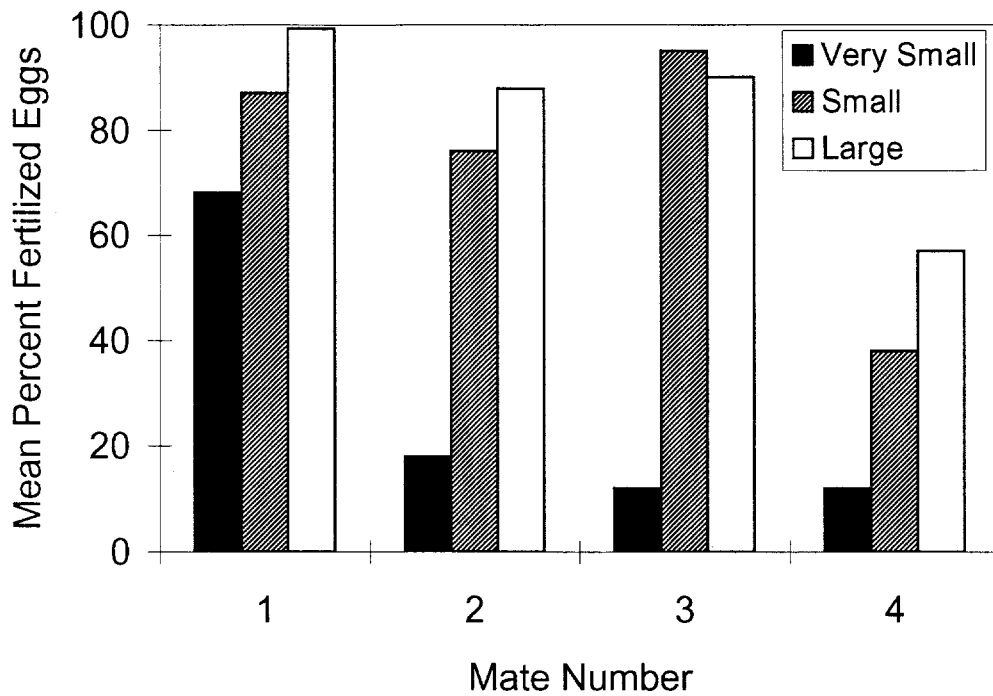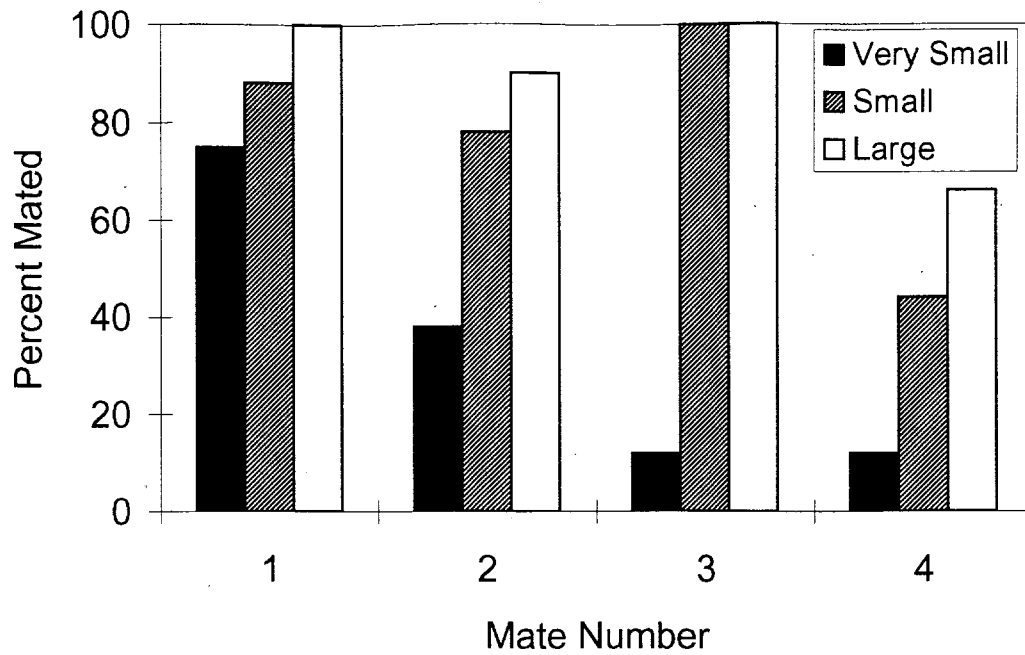
Figure 3. Percentage of females induced to ovulate (top panel) and mean percent fertilized eggs that initiated division (bottom panel) by very small (80-89 mm CL), small (130-139 mm CL), and large male red king crabs (140-204 mm CL) from mating studies conducted in the laboratory by Paul and Paul (1990, MS).
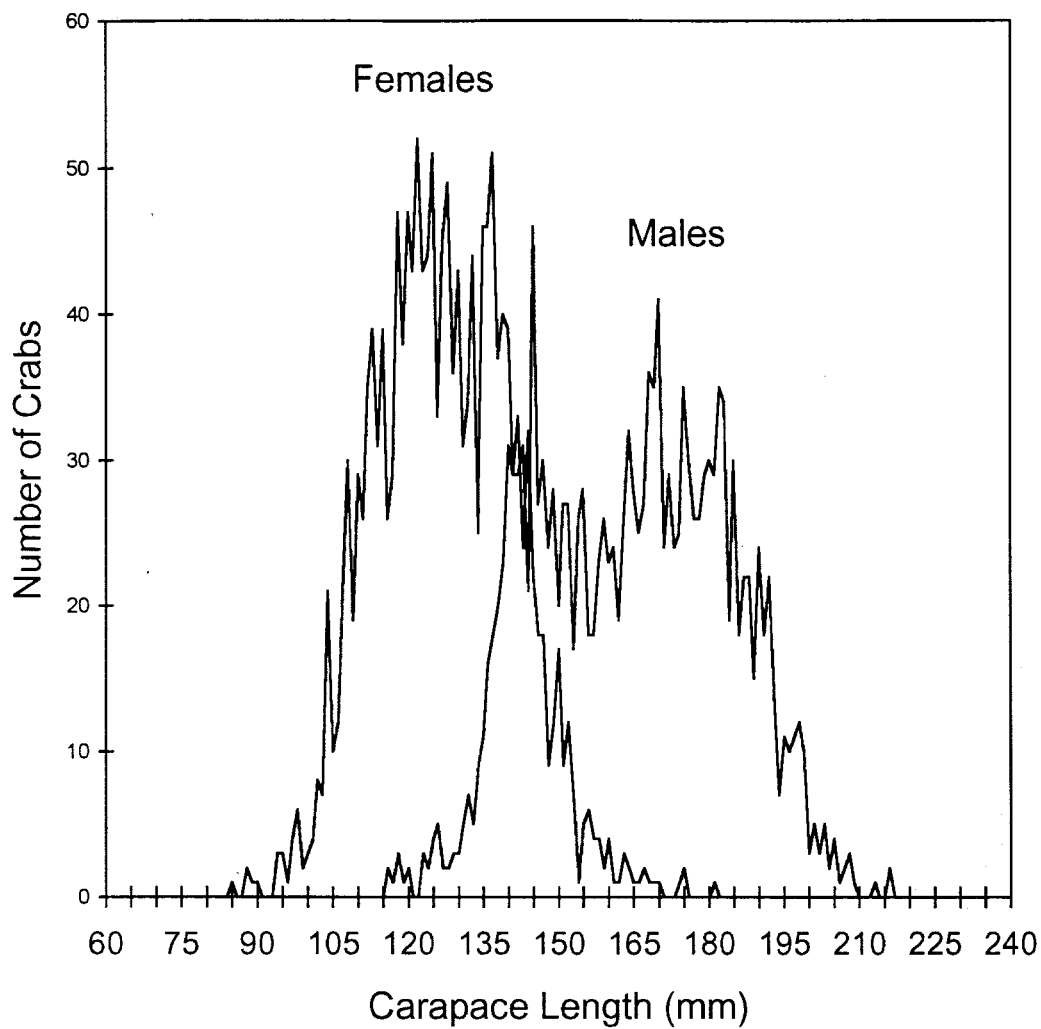
Figure 4. Length frequency distribution of oldshell male and female grasping pairs collected by Powell et al. (1973) off Kodiak Island during 1963-1971 (from Schmidt and Pengilly 1990).

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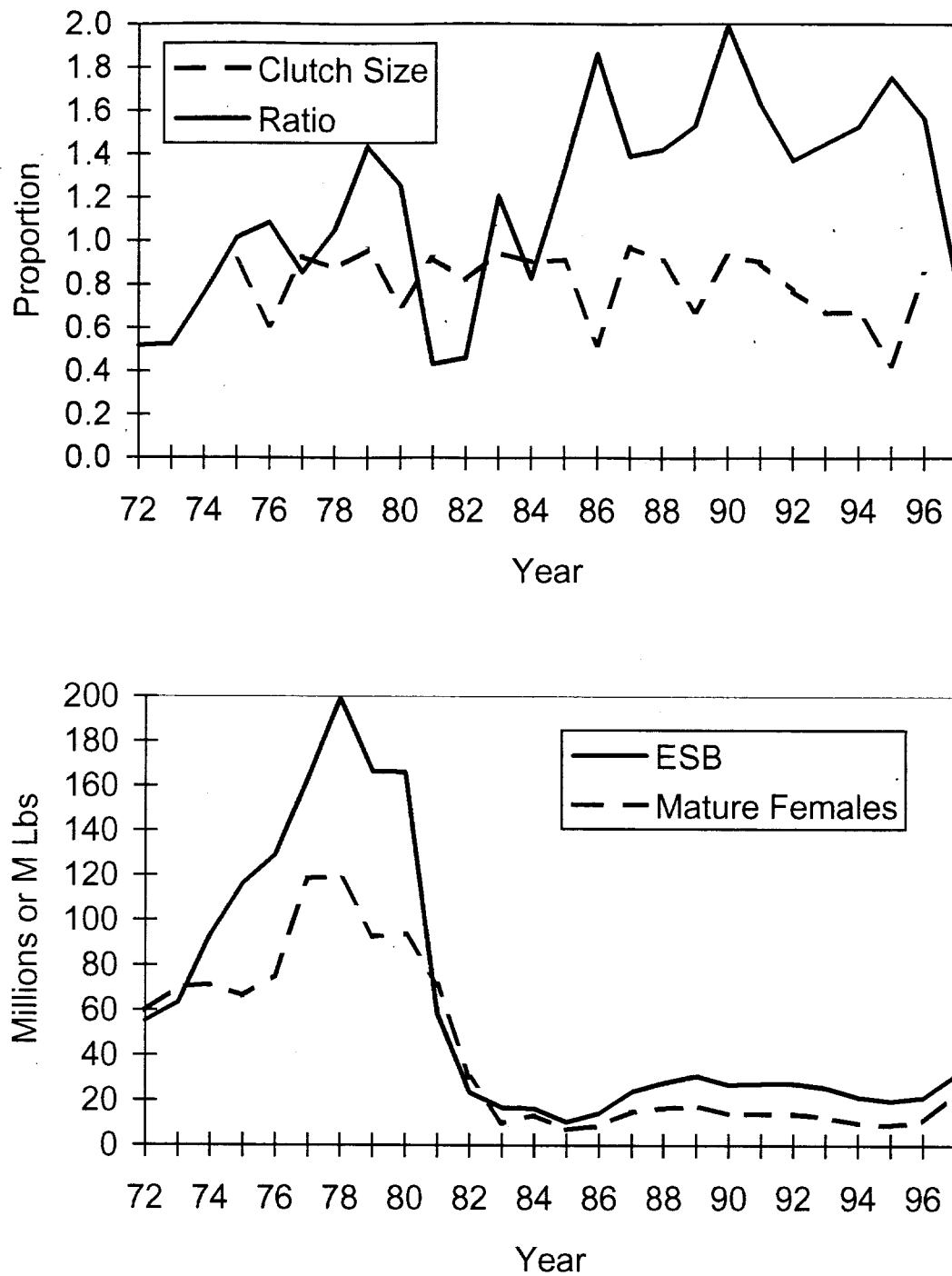
Figure 5. Estimates of mean proportionate clutch fullness and ratio of male reproductive potential to mature female abundance (top panel) and mature female abundance (millions) and ESB (millions of pounds) (lower panel). Percent clutch size was estimated from NMFS survey data, and other estimates are from LBA.
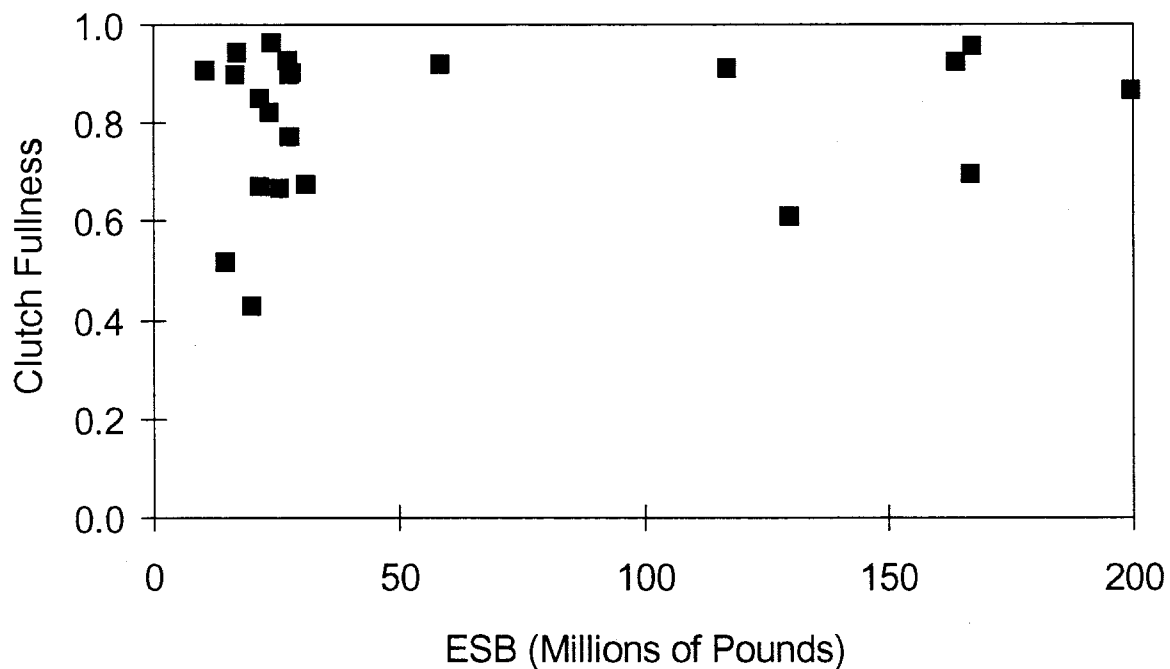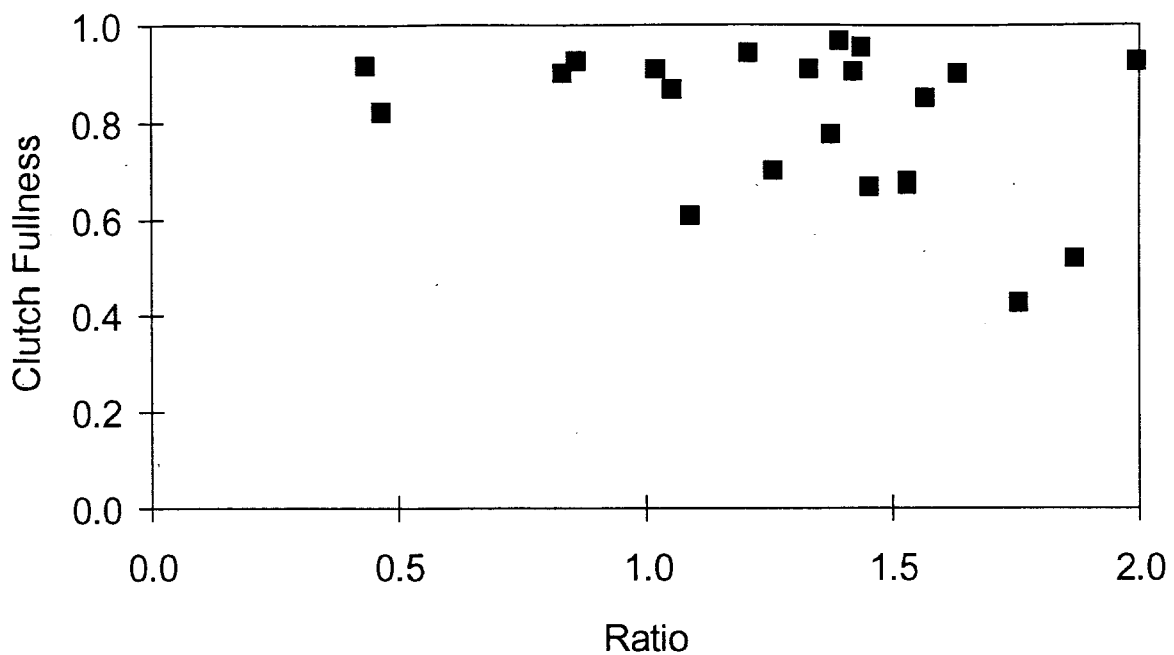
Figure 6. Relationships between mean proportionate clutch fullness and ratio of male reproductive potential to mature female abundance (top panel), and mean proportionate clutch fullness and ESB (lower panel). Clutch size was estimated from NMFS survey data, and other estimates are from LBA.
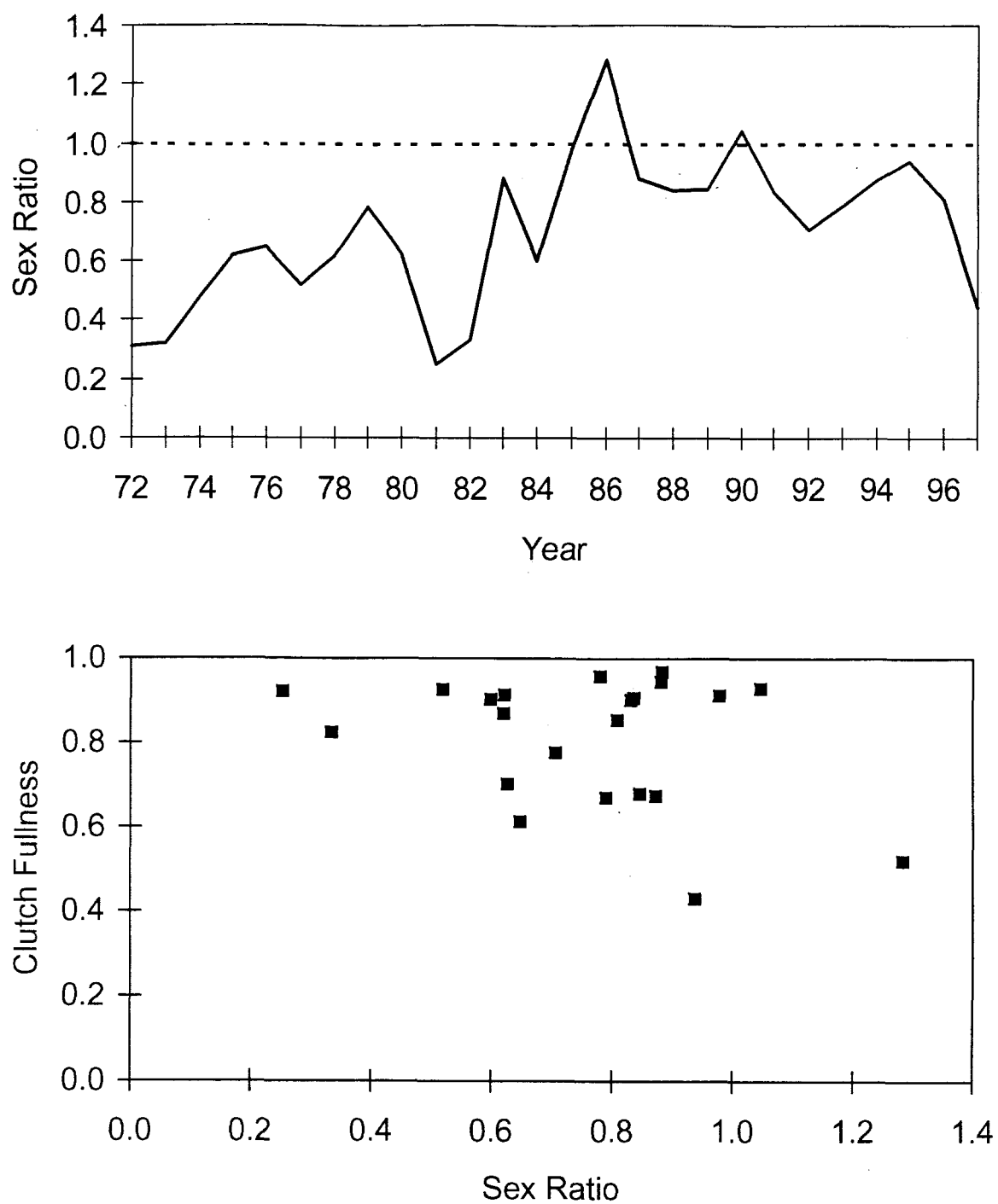
Figure 7. Sex ratio of mature male to mature female abundance (top panel) and relationship between mean proportionate clutch fullness and sex ratio (bottom panel). Clutch size was estimated from NMFS survey data, and sex ratio was estimated from LBA.